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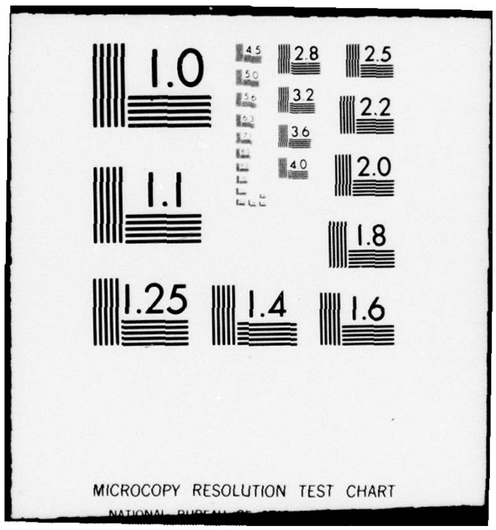
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THE APPLICATION OF
SURFACE ACOUSTIC WAVE TECHNOLOGY
TO COMMUNICATIONS SYSTEMS

THESIS

AFIT/GE/EE/78-25 Daniel T. Heale
Capt USAF

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THE APPLICATION OF SURFACE ACOUSTIC WAVE TECHNOLOGY TO COMMUNICATIONS SYSTEMS.

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Presented to the Faculty of the School of Engineering
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by

10 Daniel T. Heale, ~~B.S.~~

Captain USAF

Graduate Electrical Engineering

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Preface

The purpose of this study was to find new and innovative ways to use Surface-Acoustic-Wave (SAW) Technology in Communications Systems. In addition to investigating direct applications of SAW devices to communications systems, it was felt that by combining several processes in the SAW medium greater efficiency and flexibility would be possible. In this study, background preparation in Molecular (solid state) Electronics and Communications was combined in an effort to shed new light on systems applications of this special category of solid state devices.

This particular area of study was suggested by Dr. Paul H. Carr of the RF Components Group, Antennas and RF Components Branch of the Electromagnetic Science Division of the Rome Air Development Center. I am grateful for his sponsorship of this study and for his helpful suggestions. I am also grateful for the suggestions of Mr. Alan J. Budreau, of the same office.

I am extremely grateful to my thesis advisor, Captain John M. Borky, for his technical assistance, guidance, patience and encouragement. Without his help I might not have finished this study.

A special word of thanks goes to Captain Stanley R. Robinson, Captain Gregg L. Vaughn, and Professor Raymond S. Potter, all Professors of Electrical Engineering at AFIT School of Engineering. Captain Robinson and Captain Vaughn provided constructive suggestions while Professor Potter let me use some of his reference material.

I certainly would be remiss if I did not acknowledge the help of family and friends. My wife, Rita, and my daughter, Mary, were very

patient and understanding during my studies at AFIT. I would also like to thank Rita for typing the rough draft, and for her extra efforts in helping me during the hectic last few weeks of this study. I want to thank my parents, Mr. and Mrs. Thomas C. Heale, for their encouragement. I would also like to thank a dear friend, Mrs. Mary B. Reed, for her support and encouragement.

A final word of thanks goes to Mrs. Jeri Messenger for her extra efforts in typing the final draft.

Daniel T. Heale

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Abstract

The purpose of this study is to suggest new approaches to the use of surface acoustic wave technology in communications systems. The problem was approached by considering the basic physics of the waves and their interactions with themselves, with electrons, and with photons. Three devices that used SAW components were analyzed on the basis of the basic physics, and their performance was compared with non-SAW devices, where possible. The three devices were a SAW convolver with bidirectional amplification, an A/D converter using a SAW-generated reference waveform, and a phase-lock loop using acoustic waves for the mixing and filtering functions. Based on the analysis of those devices, new approaches are suggested. The devices suggested were a mixer that delays one input relative to a second input; a variable Q, high Q bandpass filter; and a filter that selects a signal based on an impurity pattern in a semiconductor.

THE APPLICATION OF SURFACE ACOUSTIC WAVE TECHNOLOGY TO COMMUNICATIONS SYSTEMS

I. Introduction

Surface acoustic wave (SAW) devices have already been used successfully in many communication systems. Among the most common uses are in pulse compression, band-pass filtering, time delay, and correlation/convolution (Young, 1976:691). One example of a system that uses pulse compression is a range-instrumentation, data-link system (Marple, 1976). The system uses SAW pulse compression for synchronization and for code-identification of more than 100 vehicles. Ease of implementation and processing gains of 17 dB make the SAW device a "cost effective approach", according to the author (Marple, 1976:591). A SAW TV IF filter, used in color television receivers, is an example of SAW band-pass filtering (Devries, 1976). The SAW device has better out-of-band frequency rejection (60 dB versus 50 dB), a more linear phase response, comparable reproducibility (0.2 percent) and only a slightly higher cost (the SAW filter costs between \$1 and \$2, when mass produced) than a standard IF filter (Devries, 1976:673-676). In addition, the SAW filter is smaller than a dime and requires no tuning, reducing equipment size and assembly costs. Both time delays of up to 1 msec (Coldren, 1976:598) and continuously-variable delays of up to 40 μsec (Deacon, 1973:229) are possible with SAW delay lines. A detailed analysis of a SAW convolver will be presented in a later chapter. All in all, SAW devices have been found to be useful in systems and something that systems engineers should be

aware of.

Besides the areas already presented, considerable research has been done on other aspects of SAW devices. Much work has been done in the area of SAW oscillators and resonators (Manes, 1976; Carr, 1977; Tanski, 1976; Suzuki, 1976). These devices are able to operate at frequencies of between 20 MHz and 1 GHz as opposed to a top frequency of 20 MHz for a conventional bulk mode quartz crystal oscillator. In order to reach comparable frequencies, the crystal oscillator needs frequency multipliers and filters. Consequently, at those frequencies, the crystal oscillator system has a size and weight that is twenty times that of a comparable SAW device (Carr, 1977:3-4-1). The chief disadvantage of the SAW oscillator/resonator is its long term aging (i.e., instability). Its aging is greater than 10 parts per million per year which is worse than the aging of a crystal oscillator system (Manes, 1976:716).

Work has also been done in both programmable and adaptive SAW devices. One programmable device is the SAW fast frequency synthesizer (Laker, 1976). This device uses 16 SAW filters which are all on a 25 x 9 mm substrate. The filters are selected by an array of SOS p-i-n diodes and frequencies can be switched in less than 5 μsec (Laker, 1976:693). The capability of rapidly changing frequency is particularly desirable in spread spectrum systems. Another desirable feature for spread spectrum systems is wide bandwidth. The wide bandwidth of SAW devices was particularly helpful in implementing an adaptive spread spectrum receiver (Das, 1977). SAW components are used to estimate the spectrum of a slowly-varying, wide-band Gaussian interference signal. From even this small

sampling of SAW devices and applications, it is clear that these waves have wide application.

Objective

The mission of the RF Components Group, Antennas and RF Components Branch of the Electromagnetic Science Division of the Rome Air Development Center (RADC/EEA) includes both the advancement of basic SAW technology and the application of that technology to solve Air Force system requirements. At the instigation and under the sponsorship of RADC/EEA, this thesis project was structured as a theoretical investigation of new and better applications of SAW devices in the arena of communication system signal processing.

This study sought to determine some new approaches to using SAW technology in communication systems. More specifically, it was felt that new techniques could be developed that use different combinations of the basic wave properties and interactions. Instead of examining SAW devices as just replacements components in existing communications systems, the different combinations of wave properties and interactions were examined as fulfilling a function in the communication process. Depending on the degree of abstraction used in describing the component, the two approaches might be considered the same. For example, if a component is described as a square law device, a SAW device (that uses a nonlinear-wave property) or a diode could fulfill the function even though the SAW device works in a completely different fashion. Certainly this idea of nonstandard components is not new (e.g., the SAW convolver is a nonstandard component). However, new experimental evidence, recent

demonstrations of novel devices, and new insights into previously discovered properties shed some new light on the subject.

Approach and Scope

The approach used in this study was an analytical one, since appropriate laboratory facilities for experimental verification of the concepts evolved were not easily accessible at the time the work was undertaken. Part of the study was a comprehensive literature search to determine the properties of surface acoustic waves, their limitations and how the waves had already been applied to communications systems. A survey was then made of various communications signal processing problems and techniques. The two areas were compared. A few SAW devices that used different approaches to the communications problems were singled out and analyzed from the basis of wave properties and interactions. Comparisons were made between these devices and non-SAW devices, where possible. The analyses were then extended to suggest new approaches that looked promising. A logical continuation of this work involving actual hardware and measurements would be highly desirable, given appropriate fabrication and test facilities.

Sequence of Presentation

This study begins with a presentation in Chapter II, of the basic surface acoustic wave properties and the interactions of waves with themselves, electrons, and photons. A discussion is made of the propagation direction, velocity, and frequency range of the waves. The mechanical-electrical nature of the wave is presented as well as the nature of the

surface displacement. The remaining part of the chapter deals with how the wave can be shaped and modified. Wave shaping, as a property of the pattern of a metal-film transducer, is analyzed. Modification of the wave through nonlinear wave interactions and through transfer of energy between parallel wave paths is also analyzed. Finally, the interactions of waves with electrons in a semiconductor and with photons, travelling in an optical waveguide just below the surface, are discussed.

In Chapter III the general concepts presented in Chapter II are applied to specific devices. Initially, some of the more practical aspects of the waves (such as loss mechanisms, distortion mechanisms and environmental effects) are presented. Three devices are analyzed. Comparisons are then made between the performance of the SAW devices and non-SAW devices, when possible. The practical aspects help to explain the less-than-ideal behavior of SAW components and suggest some tradeoffs that must be made.

Chapter IV extends some of the concepts brought out in Chapter III to suggest new approaches. Included in the new approaches are a mixer that can change the relative phases of the two inputs, a high Q variable-bandwidth filter, a device that uses an impurity pattern to select a narrowband (13 KHz) signal out of a wideband RF signal, and a SAW equivalent to an integrated circuit.

Chapter V presents the overall conclusions and recommendations for further study.

II. Surface Acoustic Wave Physics

The implementation of various communications systems or devices with surface-acoustic-wave technology is strongly dependent on the physics of these waves. The physics controls such things as allowable frequency range, allowable power levels for linear operation, and the efficiency of energy transfer. In addition, by understanding the properties of the waves, it will be easier to understand why some implementations are easier than others; that is, which implementations take advantage of both the strengths and weaknesses of the SAW approach. The properties of waves and their interactions presented in this chapter are the ones that have been useful in actual devices. The specific properties to be discussed include a general discussion of the basic wave properties, wave transductions, interactions between surface waves, interactions between surface waves and electrons, and interactions between surface waves and photons. Specific device applications will be discussed in later chapters.

Basic Wave Properties

To better understand the SAW devices, one should first have a good understanding of surface acoustic waves. The following is a summary of some important SAW properties (Slobodnik, 1976:581-594). The waves have frequencies of between 10 MHz and 1 GHz, velocities around 3×10^3 m/sec and, consequently, wavelengths of between 1 and 300 μm. The

lower limit on wavelength (upper limit in frequency) is determined by the method of generating the waves. The most common method of generating surface acoustic waves uses periodically-placed metal strips, which are collectively called an interdigital transducer (IDT) (See Figure 1). Thus, for an IDT, the achievable lower wavelength limit is determined by the resolution in the manufacturing process (Hays, 1976:658). The upper wavelength limit is determined by the length of the crystal material.

A typical crystal material (substrate) is a few millimeters thick and has a surface area of a few tens of square centimeters. Most of the wave energy is confined to one acoustic wavelength from the surface. In order to obtain more specific information about the wave properties (such as exact wave velocity), a set of equations involving the crystal properties, Maxwell's equations, and the equations of motion (relating the spatial derivatives of stress to the time derivatives of displacement) must be solved. The crystal properties include the piezoelectric constants, dielectric constants and elasticity constants. The solution also involves the boundary condition of a free surface.

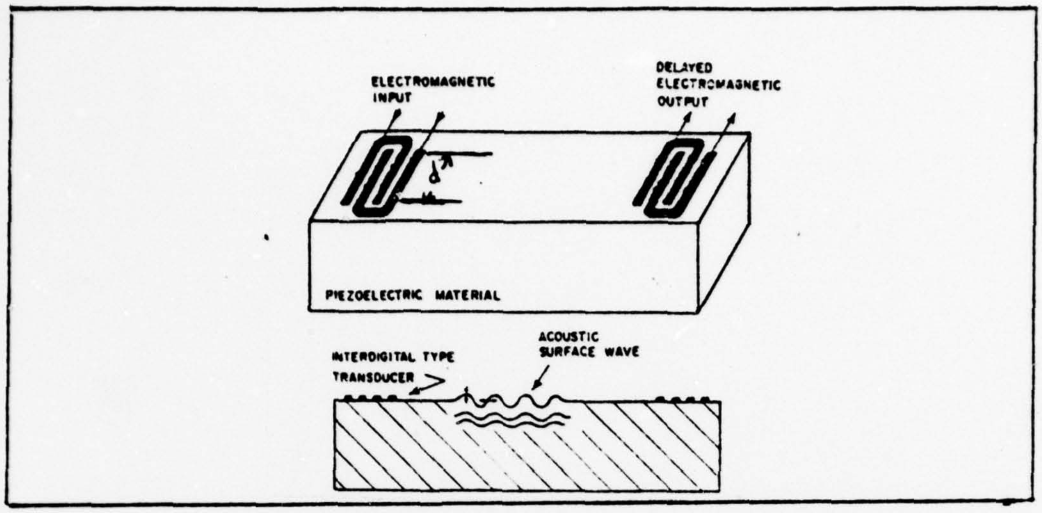

Figure 1. Schematic representation of the launching and propagation of a surface acoustic wave (Slobodnik, 1976:581).

A closed-form solution of these equations is not possible (Slobodnik, 1976:582). Part of the problem is that the crystal properties must be treated as tensors (i.e., the crystals do not have isotropic properties). The equations also lead to a transcendental equation which must be solved by computer iterative techniques. A result of the computer solutions is that the wave parameters vary with the direction of propagation. Data must then be plotted versus propagation direction. One way of denoting the direction of propagation is to specify the crystal plane and some direction on that plane. Parameters can then be plotted versus the angle the propagation direction makes with that reference direction in the plane. This method is illustrated in Figure 2.

Figure 2 shows some of the more important data obtained from the computer solution. The surface velocity determines how long the wave will be on the crystal, which is important in determining timing interfaces with

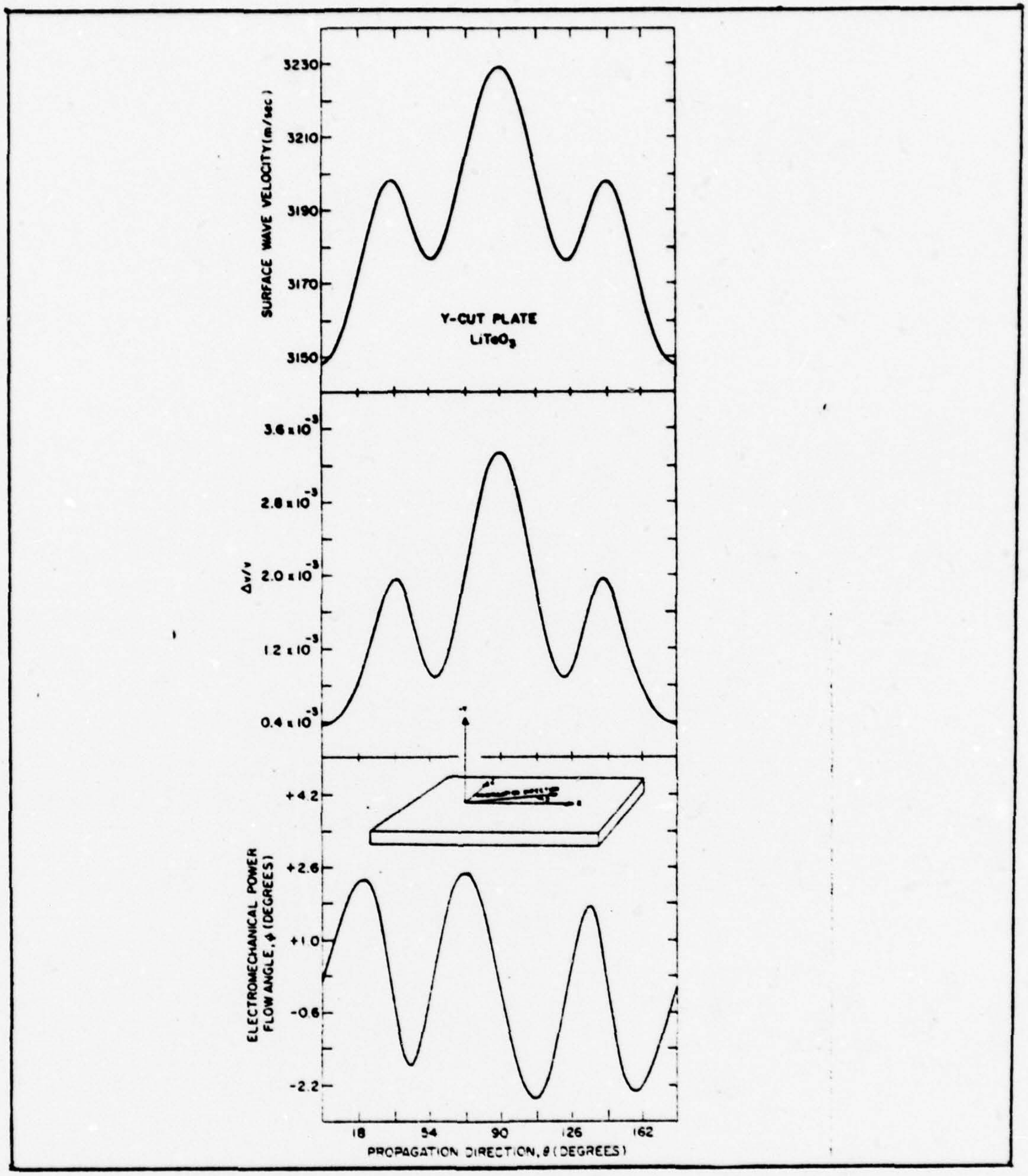

Figure 2. Velocity, $\Delta V/V$, and power flow angle curves for Y-cut $LiTaO_3$ (Slobodnik, 1976:583).

other parts of the system in which the SAW component is used. The term "$\Delta V/V$ " is defined as the percentage difference in wave velocity between a free surface and one with an infinitesimally thin perfect conductor. The $\Delta V/V$ parameter is important in describing the strength of electric field

in the wave as well as the efficiency of the wave generation process (This parameter is discussed in more detail below). The power flow angle, ϕ, is the angle between the time average electromechanical power flow vector and the direction of propagation. The natural propagation directions (pure-mode axes) are defined by $\phi = 0$. The slope of the curve determines the beam-steering (i.e., how the beam will react to slight misalignment of path) and the diffraction (i.e., how the beam-energy spatial profile will widen as the wave propagates). Minimum beam steering occurs when the slope equals zero. It can be shown that if the slope equals minus one, there is minimum of diffraction (Slobodnik, 1976:588).

Further elucidation of the $\Delta v/v$ parameter is appropriate, in the view of its central importance in determining SAW device behavior. The Δv results from the change in velocity caused by a surface coating of an infinitesimally-thin perfect conductor. The effect of the conductor (Adler, 1971:115) is to neutralize the electric field of the wave caused by the piezoelectric effect. The conductor allows free charges to move along the crystal surfaces and thereby reduces the electric field to zero. The wave then becomes a pure mechanical wave. Since the wave had some of its energy stored in the electrical potential, there is an energy loss. The result of the reduction of energy stored in the wave is a decrease in its wave length and velocity. Experiments have shown that the percentage change in velocity is directly related to the percentage of energy of the surface wave stored in its electric field (Collins, 1968:312-313). This percentage is important because, as will be seen later, SAW devices rely heavily on the strength of electric field. Also, since the waves

are generated by the reverse piezoelectric effect, $\Delta V/V$ determines the efficiency of generation process. The process is less than totally efficient because part of the energy of the generating electric field goes into the "mechanical wave" rather than the electric field of the wave.

Besides the mechanical-electrical aspect of the wave, there is another complication. The displacement is two dimensional: there is a component of the displacement parallel to the propagation direction and a second component that is normal to the surface (Viktorov, 1967:6). They are called the longitudinal and transverse components respectively. As used here, transverse will exclude any component not normal to the surface (i.e., a component perpendicular to the direction of propagation but along the surface). The path of a molecule on the surface is elliptical as the wave passes. These acoustic surface waves are examples of a more general type of surface wave, called Rayleigh waves. Rayleigh waves include water waves and earth tremor waves, and are characterized by elliptical surface-molecule movement. Since the displacements are two dimensional, there are longitudinal and transverse electric fields associated with the acoustic surface wave as well.

It will be useful for later discussions of SAW device behavior to develop the nature of the piezoelectric effect in more detail. The piezoelectric effect is a phenomenon in which pressure on a surface or displacement of a surface, with attendant stress induced in the material, creates an electric field. The reverse piezoelectric effect is observed when an electric field causes a displacement which is linearly proportional to the applied voltage and directly related to the voltage polarity (i.e., is an odd function). In contrast, the electrostrictive-effect strain

(and displacement) is porportional to the square of the voltage and is an even function. The piezoelectric effect is based on a stress-induced dipole moment within the crystal. Electrostrictive effects are normally much smaller than piezoelectric effects, so the latter are preferred as the basis for effective transducers (Mason, 1950:1).

<u>Generation, Wave Shaping and Detection</u>

The basic structure of an interdigital transducer is illustrated in Figure 1. An electrical input is applied between the two sets of electrodes on the left of Figure 1. The applied voltage causes a displacement of the surface due to the reverse piezoelectric effect. That displacement propagates along the surface as a wave according to the basic properties already presented. The transducers' chief advantages are the simplicity of construction and the wide variety of transducer responses available. Construction involves deposition of a thin metal film and patterning by means of a masking step (normally using photolithography) and by chemical etching to define the transducer geometry (Maines, 1976:640). These processes have been well developed in the integrated circuit industry. The transducer response, then, is a function of the metal pattern. The main characteristics (Hurlburt, 1974:84-85) of this pattern are finger (electrode) width, interdigital spacing, apodization (or the length of overlap of adjacent fingers) and the total length of the transducer (along the direction of propagation). In Figure 1 the apodization is uniform and is annotated by the distance d. Because each finger is connected to one of the two bus bars, the transducer length will directly affect the duration of the transducer response to an impulse excitation, and since the impulse response is related to the frequency response, the transducer length also affects the frequency response of

the transducer. The frequency response of the transducer is defined as the frequencies that are converted from the input to the wave as well as their relative magnitudes. Specifically, the length and apodization are related to the transducer bandwidth. More energy is transduced by a given finger pair when the length of overlap is increased. Thus, changing the apodization in the pattern places different energies along the acoustic path, and this "weighting" of the time response also controls the frequency response. More specifically, to a first approximation, the apodization pattern is a discrete Fourier transform of the desired frequency response of the transducer. It should be noted that for simple interdigital transducers, such as the one noted in Figure 1, the frequency response is fixed once the metal pattern is established.

Thus far, the motion of the acoustic wave has not been considered. If the transducer input is periodic, wave reinforcement is possible as the signal moves through the metal pattern. Reinforcement will occur when the time period of the input and the "spatial period" of the pattern coincide. These two periods are related by the velocity of the wave. "Spatial period" refers to the distance between the center lines of consecutive interconnected fingers. Spatial period is also related to the previously mentioned interdigital spacing, or the spacing between electrodes. It can also be shown that finger width and interdigital spacing can determine the harmonic frequency response of the transducer (Hurlburt, 1974:84; Egan, 1969:1014).

There are other ways to affect the frequency response as well as the phase response of the transducer. By the phase response, it is meant

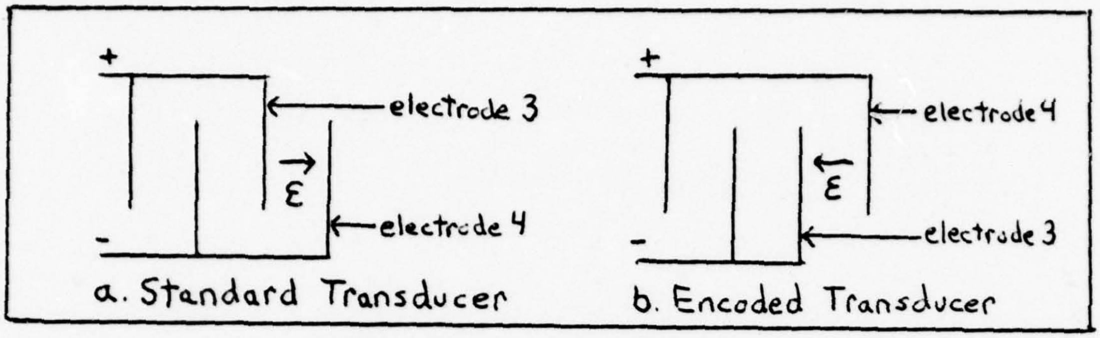

Figure 3. Transducer Encoding

how the phase of the input and the phase of the wave are related. One is to change connections to the bus bars (See Figure 3). Let one bus bar be labeled "+" and the other "-", for convenience. By switching a pair of bus bar connections (i.e., by connecting electrode 3 to - instead of + and by connecting electrode 4 to + instead of -) the direction of surface displacement is reversed since the direction of the electric field, $\mathcal{E}$, is reversed. This is equivalent to a half wavelength "phase shift" for a perfectly symmetrical, periodic wave. In that sense, bus bar connections can be thought of as "bi-phase coding" of the transducer (De Vito, 1971:1523-1525). A more general way of modifying the response is by individually weighting the amplitude and phase of each electrode (Hagan, 1974:177-180), rather than connecting them with a bus bar.

Another property of the transducer is directly related to the wave properties of the generated signal. When the electric field is applied to the interdigital transducers, waves are generated simultaneously in opposite directions (Slobodnik, 1976:585). This wave effect is similar to the effect of vibrating a long board on the surface of a pond. Since the acoustic waves (propagating in opposite directions) are identical,

half the energy is lost if only one output transducer is used. The misdirected wave is normally absorbed by placing a piece of wax on the surface of the appropriate side of the transducer.

In order to get an electrical output, a second transducer is necessary. This output is produced by the inverse of the wave generation mechanism. The wave has an electric field associated with it (due to the piezoelectric effect). The wave produces a potential difference between the electrodes of the two bus bars. The electric output is, then, the voltage between the two bus bars. A maximum output occurs when the wave coincides with the electrode positions; that is, when the wave crests coincide with the position of one set of electrodes (i.e., connected to one bus bar) while the wave troughs coincide with the position of the other set of electrodes (Maines, 1976:644).

Interaction of Waves in the Piezoelectric Medium

The method of wave interaction plays an important role in surface-acoustic-wave physics. For low power densities, the medium is linear and the superposition principle can be applied. As with most wave phenomena, however, there is a power density above which the wave interaction becomes nonlinear. As an example, for Y-cut, Z-propagating $LiNbO_3$ at 905 MHz, the wave interaction becomes nonlinear when the total power density is around 10 mW/mm, and at 83 MW/mm the power in the second harmonic is only 7 dB below the power in the fundamental frequency (Slobodnik, 1969:203). At the higher power densities the wave displacement is also affected by the higher powers of the electric-field magnitude at the point of displacement (e.g., the square of the total electric-field magnitude). Thus, when two

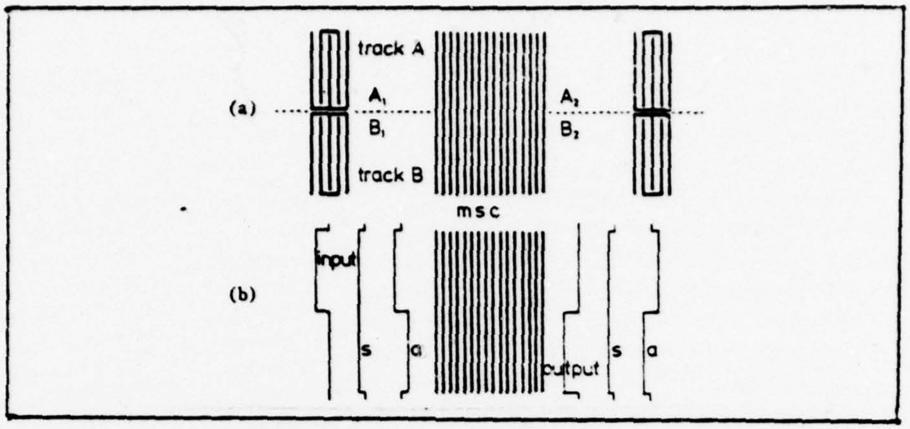

Figure 4. (a) Schematic of multistrip directional coupler.
(b) Input and output field distributions resolved into symmetric s and antisymmetric a modes. (Marshall, 1973:125)

waves interact, the displacement will be proportional to the weighted sum of several terms, each of which is related to the electric field of one wave, or the electric field of the other wave, or to both fields. There are terms proportional to each electric field separately (the linear piezoelectric effect), terms proportional to the square of each of the electric-field magnitudes, one term proportional to the product of the two field magnitudes, plus higher order terms.

Waves on two separate (but parallel) paths (or tracks) can be made to interact by the use of thin metal strips (See Figure 4a), called a multistrip coupler (Marshall, 1973:125). Like the interdigital transducer, the metal strips are used to establish electric fields on the piezoelectric surface. However, unlike the IDT, these metal strips are not connected to anything so charge flows only when there is a temporary difference between the electric potentials of the tracks. The charge flow causes energy to be transferred from one track to another.

To simplify the analysis, it is assumed that the electric field of the acoustic wave is uniform across a track (i.e., is uniform perpendicular to its direction of propagation). Diffraction and beam steering, which were discussed previously, may cause some deviation from this simple model. If the wave in each track is modeled as uniform across the track and there are two tracks, any instantaneous input to the metal strips can be described as a linear combination of two linearly-independent input waveforms. One set of linearly-independent input waveforms could consist of a waveform with unit amplitude on one track and zero amplitude on the second track and a second waveform with unit amplitude on the second track and zero amplitude on the first track.

However, an equally acceptable set is pictured in Figure 4b, and is specified by the letters "s" and "a". Waveform "s", standing for symmetric, is uniform across both tracks. The second waveform "a", standing for antisymmetric, has a unit-amplitude electric field on one track and a field in the second track that is equal in magnitude, but opposite in direction from the first track. The only criteria for two waves to be linearly independent is that one is not a multiple of the other. The reason for preferring the set in Figure 4b over other sets is that the form of these waves is preserved in going through the multistrip coupler, regardless of the number of metal strips.

A reexamination of the energy-transfer mechanism and of the basic wave physics will help to explain why the waveforms are preserved (Marshall, 1973:125). It was previously stated that energy is transferred only when there is a temporary difference in the electric potentials of

the two tracks. Since, by definition, the "s" wave has a uniform electric field across both tracks, that potential difference does not exist. No energy is transferred. The symmetric wave is not changed at all by the presence of the metal strips.

A temporary potential difference does occur, however, for the "a" wave. The presence of the metal strips allows energy transfer, for that case. Since the two electric fields have equal magnitude but opposite sign (by definition), the transfer of electrons causes a cancellation of the electric field in each track. The wave continues travelling because there is still the purely mechanical part of the wave. It should be noted that this cancellation occurs only while the wave is under a metal strip. In between the strips the mechanical wave still generates an electric field due to the piezoelectric effect. As was explained in the discussion of $\Delta V/V$, the purely mechanical wave and the regular acoustic surface wave travel at different speeds. But since the metal strip pattern is the same on both tracks the wave undergoes the same velocity changes over both tracks. The relative position of the wave section in each track remains the same, so the "a" wave is pass through undistorted, but delayed in time, relative to the "s" wave.

From an analytical aspect, then, it is the relative delay that determines the amount of energy in each track. For the case in Figure 4b, complete transfer requires a relative delay of a half period between the "a" and "s" waves. The period referred to is the period of the input wave. In Track A the crest of the "s" wave would coincide with the trough of the "a" wave. If the two displacements matched exactly, there would be

total wave cancellation, including the mechanical part of the wave. In Track B the two crests coincide so constructive interference occurs. It should be noted that the "s" and "a" waves are just an analytical tool to simplify the real situation. There are not two waves that actually interfere. Still, a useful analogy can be made between sound waves of different frequencies and the "a" and "s" waves (that travel at different velocities) (Marshall, 1973:125). The beating of the sound waves is analogous to the "interference" of the "a" and "s" waves and the analogy helps to predict the amount of energy transfer.

The periodicity of the metal strips also affects the transfer of energy (Marshall, 1973:125). When the spatial period of the wave matches the period of the strips, all the strips in contact with the wave will have the same potential. This fact follows from the definition of periodicity and the linkage of displacement, stress, and electric field in a surface acoustic wave: the electric field associated with the wave will have the same value at intervals equal to one period. Since the strips all have the same potential, no electric field will exist between the strips. With no electric field present between the strips, a surface acoustic wave cannot be generated in the adjacent track. Therefore, there is a stopband for the strips associated with the input frequency that corresponds to the spatial period of the strips.

Other Interactions

In addition to the interactions of the surface acoustic waves with themselves (either directly or indirectly), these waves can affect the flow of electrons in semiconductors (Lee, 1973:4807-4812). The semi-

conductor can be separated from the piezoelectric material by a small distance or it can be identical with it (i.e., a semiconducting piezoelectric material). The former is called a separated medium while the latter is called a combined medium. Structures also exist in which a semiconducting film is deposited on a piezoelectric substrate. In either case the electric field of the surface wave causes electrons or holes to move. Their velocities are the product of the total electric field present (both ambient and from the wave) and the appropriate carrier mobility. The total current is, then, the sum of all the charges times their velocities.

Nonlinear interactions will occur if both the charge distribution and the charge velocity are affected by the electric field of the surface acoustic wave. The semiconductor current will then be proportional to the square of the electric field of the wave. This nonlinearity will occur when the velocity of the electrons or holes is approximately the velocity of the wave, provided the concentration of electrons (or holes) is great enough to be significant. The effect of the relative velocities of the charge carriers and the wave on charge distribution can be seen more clearly by examining the extremes. If the charge carrier velocity is much greater than the wave velocity, the charges will move to neutralize the effect of the electric field of the wave before the wave can move significantly. Since the electric field of the wave is effectively neutralized, the current will not be proportional to the square of the field even though the charge distribution will be proportional to the electric field. At the other extreme, when a wave is moving much faster than the charge carriers, the carriers cannot distribute themselves fast enough to be affected by the electric field of the wave. Therefore, the charge

distribution is not proportional to the waves' electric field.

Another type of interaction can occur between a surface acoustic wave and light in an optical waveguide. The surface acoustic wave causes an instantaneous change in the density of the medium surface. Since the index of refraction light is, to first order, proportional to the density of the medium (Yariv, 1971:306), the light will be reflected at different angles by the variations of the acoustic wave. This effect is called Bragg diffraction. The movement of the wave will also add a small doppler shift to the frequency of the light.

Conclusion

In this chapter some of the basic properties of surface acoustic waves were presented. The wave travels along certain preferred directions on the crystal-substrate surface, at speeds approximately five orders of magnitude below the speed of light. Transduction of an electrical signal to a wave is done through an easily-manufactured metal pattern and this pattern is varied to shape the wave. Waves can interact with waves on the same track, with waves on parallel tracks, with electrons in semiconductors, and with photons in an optical waveguide. All these properties can be useful in actual devices. The usefulness of these properties, as well as some properties that degrade performance, will be discussed in the next chapter. Specifically, three SAW devices will be analyzed, using these basic properties as a guide.

III. Analysis of SAW Devices

In this chapter the basic properties and interactions of surface acoustic waves are applied to systems and the performance of these systems is compared to that of non-SAW systems. Three systems that use SAW components will be studied: An analog-to-digital converter, a convolver with bi-directional amplification, and a phase-locked loop. These applications of SAW devices show innovative approaches in which the characteristics of SAW technology may yield significant improvement over conventional designs. In order to better understand the comparisons, it will be necessary to present some of the loss mechanisms, distortion mechanisms and environmental effects in SAW devices.

Additional SAW Loss Mechanisms

Some of the loss mechanisms were briefly presented in Chapter II. These include the 3 dB loss due to the bidirectionality of the transducer and the misdirection of energy due to diffraction and beam steering. In addition there are propagation losses and transduction losses. Propagation losses occur due to interactions of the wave with phonons (thermally excited elastic waves), crystal/surface defects, and any material adjacent to the crystal surface (Slobodnik, 1976:585). Losses from the first mechanism can be reduced by lowering the temperature. The second mechanism can be significantly reduced by polishing the surface and by carefully controlling crystal growth. Loss reduction for the third mechanism (called air loading or mass loading) involves reducing the mass

in contact with the surface. This can be done by encapsulating the surface in a vacuum or in a light gas (e.g., Helium) and by replacing heavy metal films with lighter metals, for example, replacing gold electrodes by aluminum electrodes. The combined losses due to the first and second mechanisms are proportional to the wave frequency squared while the losses due to the third mechanism are linearly proportional to the wave frequency.

Transduction losses are associated with the matching of an energy source and the transducer. The transducer can be represented by an equivalent circuit consisting of a parallel combination of a capacitance and a frequency-dependent admittance (Smith, 1969:856-864). The latter is called the acoustic radiation admittance. Impedance matching is achieved through the use of a tuning inductor. At least half the energy from the source is lost in the impedance matching. Additional losses occur through the parasitic capacitance of the input leads and the small resistance of the electrodes. The capacitance in the equivalent circuit is associated with the interdigital metal pattern while the acoustic radiation admittance is associated with the travelling wave itself.

Reflections in SAW Devices

Distortion mechanisms are also present in surface-acoustic-wave devices. Reflection is one such mechanism. Like most waves, surface acoustic waves are reflected at discontinuities in the wave medium. The discontinuity could be in either the mechanical or electrical properties of the medium. Mechanical discontinuities include grooves or overlays of some material as well as the diffusion or ion implantation of impurities to deliberately change the substrate properties. In addition to the

mechanical discontinuity caused by a metal-electrode overlay, the electrode shorts the electric fields of the wave, causing an electrical discontinuity. Distortion occurs when the reflection interacts with an incoming wave so that the two cannot be distinguished. One particularly troublesome reflection that results in distortion is worth mentioning. More exactly, two reflections are involved: A wave, coming from input transducer, is reflected by the output transducer back towards the input and is then rereflected by the input transducer back toward the output transducer. This is called triple transit because the wave traverses the surface three times before it is received.

Although reflections can cause distortion, they can also be useful. Since the reflection coefficient of grooves is proportional to the depth of the groove times the wave frequency (Williamson, 1976:703), reflections can be used to selectively reflect portions of large-bandwidth signals. The allowed bandwidths are related to the fractional bandwidth of the surface acoustic wave. For example, at a center frequency of 100 MHz, even a 1 MHz bandwidth would only be 1 percent of the center frequency. Since reflection is proportional to frequency and since frequency, in the example, varies by only one percent, the reflection also varies only one percent over the allowed frequency range of the signal. For further information on the selective reflecting of signals see Dolat, 1974 in the bibliography. Besides signal separation, reflectors can be used for signal reinforcement.

The SAW resonator is an example of SAW relective reinforcement by reflection (Bell, 1976:711-721). The resonator consists of two sets of reflectors plus an input transducer and an output transducer. Waves

reflect off both reflectors and add constructively only for a specific frequency. This frequency is determined by the distance between the reflector sets, and the structure is the acoustic equivalent of a Fabry-Perot cavity. As an example of performance, some SAW resonators have fractional bandwidths as low as 0.0001 (Bell, 1976:711; Staples, 1974: 280-285).

Environmental Effects

One environmental factor that affects surface acoustic waves is temperature. Like most physical objects, temperature changes the properties of the crystal. These temperature-dependent properties include the elastic, piezoelectric and dielectric constants as well as the mass density (Slobodnik, 1976:583). Since these properties help determine wave velocity (see Chapter II), the wave velocity will also vary with temperature. Velocity variations are normally in the 10 ppm/^{o}C to 100 ppm/^{o}C range.

Vibration is one environmental factor for which SAW devices have an advantage over devices using crystals. In one experiment (Weglein, 1977:103-104) the performance of a periodic-grating SAW oscillator in a vibration environment was compared to that of a voltage-controlled quartz crystal oscillator. The SAW oscillator had reflectors (i.e., periodic-gratings) to limit the frequency range but used a non-SAW amplifier for feedback. Both oscillators were run at 97 MHz and frequency multiplied up to 9.3GHz; noise was then measured, for both oscillators, from 0 to 20 KHz away from the 9.3 GHz frequency. Without vibrations, the quartz crystal oscillator had 5 to 20 dB less noise than the SAW

oscillator over the frequencies indicated. With vibrations of 8 G rms at 20 to 2000 Hz, the SAW oscillator was relatively unaffected. The quartz crystal oscillator, however, had noise of 30 to 40 dB above its quiescent condition, and spikes of up to 20 dB more, in some places.

These noise qualities have definite systems implications. Crystal oscillators must have sophisticated suspension systems to reduce the vibrations, and care must be taken to minimize the vibration effects. No such effort is required in making the SAW oscillator less sensitive to vibration. There are two reasons why SAW oscillators are naturally less sensitive to vibrations. The substrate is thick (compared to the wavelength of the vibration), and it is firmly supported on a rigid base. Although the results quoted were for a periodic-grating SAW oscillators, the authors of the article anticipated similar results for other SAW devices.

A neutron-radiation environment most significantly affects a SAW device which uses SAW-semiconductor interactions (Berg, 1976:1648-1653). The neutron radiation affects the interactions by changing the properties of the semiconductor. Specific changes in these semiconductor properties include reducing the number of free carriers, charging surface states (impurities) in semiconductor-oxide interfaces, and decreasing the carrier mobility (Rickets, 1972:176-177). In Chapter II, the SAW-semiconductor interaction was characterized by a current in the semiconductor which was the sum of all the charges times their velocities. By reducing the number of free carriers, the net charge is reduced, thus the interaction current is reduced. Similarly, reducing the carrier mobility

reduces the interaction current by decreasing the charge velocity (since velocity is proportional to mobility, when the electric field is constant). Surface states affect the ambient electric field at the surface. The effect of the surface states, then, is to change carrier velocity.

In one experiment (Berg, 1976:1649) four convolvers using SAW-semiconductor interactions were irradiated with neutrons and tested for permanent damage. The convolver will be the first SAW device to be discussed in detail below, so only the performance degradation will be discussed here. Both separated medium and combined medium devices were tested. The combined medium device used CdS and had a rapid decrease in performance at a neutron fluence of 20×10^{13} neutrons/cm^2. Performance degradation was due to decrease in carrier mobility and the number of free carriers. The degradation of performance in the separated medium devices was primarily due to decreases in the number of free carriers. A device using Si and $LiNbO_3$, separated by an air gap, showed immediate degradation with neutron fluences as low as 1×10^{13} neutrons/cm^2, and the degradation gradually increased with increasing neutron fluence. A separated-medium convolver using polycrystalline silicon on top of $LiNbO_3$ had a marked decrease in performance for neutron fluences of 50×10^{13} neutrons/cm^2 and greater. Another convolver that used ZnO on top of SiO_2 (which was on top of the silicon) had degradation for neutron fluences of 20×10^{13} neutrons/cm^2 and greater. The increased susceptibility of the ZnO-SiO_2 - Si convolver to neutron radiation was due to the effect of the charged surface states in the SiO_2 - Si interface.

Like the reflections, the charged surface states can be useful when

they are controlled. In one device (Coldren, 1975:137-139) the charging process was controlled by placing a DC bias on the output electrodes of a $ZnO-SiO_2$ -Si convolver. In this case, the charge was injected into the surface states of the metal -ZnO interface. The stored charge was directly related to the largest applied bias and remained for periods up to 1 day. The effect of the stored charge was to selectively weight the SAW-semiconductor interaction by determining the ambient electric field. A consequence of this effect was that the charge pattern could be "read out" when an impulse was applied to one transducer of the convolver and a "long" pulse was applied to the other transducer.

SAW Convolver

The reason that the convolution of the impulse with the long pulse gives the stored charge read out, is directly related to the process of convolution. The convolution, C(t), of two signals r(t) and s(t) is given by

$$C(t) \triangleq \int_{-\infty}^{\infty} r(t-\tau)\, S(\tau)\, d\tau \tag{1}$$

The most direct way to implement the convolver is to take the two signals as inputs, (one of which is inverted in time), bring the two signals together (change t) and multiply their magnitudes on a point by point basis, and integrate (or sum) the products. The SAW convolver uses this implementation (See Figure 5).

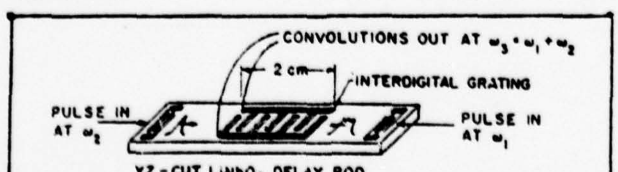

Figure 5. SAW Convolver (Kino, 1976:729)

The product of the inputs is obtained through the mechanism of nonlinear wave interaction, presented in Chapter II, and the total non-linear signal is detected by the output transducer. In the $ZnO-SiO_2$ -Si convolver just described, the stored charge weights each product along the path. In that example, let $r(t) = \delta(t)$, $s(t) = C$ = constant over some finite path length and $w(t)$ be the weighting function of the stored charge. Then equation (1) becomes

$$C(t) = \int_{-\infty}^{\infty} w(\tau)\ r(t-\tau)\ s(\tau) = \int_{\text{interaction length}} w(\tau)\ \ (t-\tau)\ C\ d\tau = Cw(t) \qquad (2)$$

The above result is the convolution as long as the impulse is under the output (center) transducer. Notice that the weighted convolution is the stored charge distribution.

On a more mathematical basis (Kino, 1976:728), consider the inputs as two traveling waves whose electric fields have the form $\exp\ j(wt \pm wz/Va)$, where w is the wave frequency, Va is the acoustic velocity, t is time and z is the position along the surface. From Figure 5, the wave traveling to the right is of the form $\exp\ j\left[w_2 t - w_2 z/Va\right]$ while the wave traveling to the left is of the form $\exp\left[j\ w_1 t + w_1 z/Va\right]$. The product of the two (the cross product term of the non-linear interaction) will have the form $\exp\ j\left[(w_1+w_2)\ t-(w_2-w_1)t/Va\right]$. Letting $\tau = t - z/Va$, the form becomes $\left\{\exp\ j\left[w_1(2t-\tau)\right]\right\} \exp\left[j\ w_2 \tau\right]$ which is of the general form of $r(t-\tau)\ s(\tau)$ but with the time scale weighted by 2. As long as the output transducer can detect the total product signal at all points, the output will be the sum of all the products and, hence, the convolution. To detect the signal, the transducer must cover the entire area of interaction and must

have a spatial period equal to that of the wave (i.e., proportional to w_2-w_1/Va). Notice that if $v_1 = v_2$, the product will be independent of position, so it can be detected with just a metal plate. This is called the degenerate mode.

Some typical parameters of a SAW convolver will be helpful in assessing its value in systems applications. First, a figure of merit for a convolver can be defined as $F = P_3/P_2P_1$ where P_3 is the RF output power, and P_1 and P_2 are the input powers. For a typical $LiNbO_3$ convolver (Kino, 1976:729) in the 100-200 MHz frequency range with a beam width of 1.27 mm and an output transducer 2 cm long, the figure of merit is around -83dBm. In a signal processing operation, the system would normally convolve the received signal with a known standard signal (internally generated). The known signal can then be set to a power level that does not generate appreciable harmonics. The typical F, then, implies that the output is 63dB lower than the input (for one input at 20 dBm). If the input signal level is also restricted to 20 dBm (because of saturation considerations), then the highest output signals would be -43dBm. If the noise level in the processor receiver was -90dBm, this would give a dynamic range of -43dBm - (-90dBm) or 47 dB.

Before describing the SAW convolver with bidirectional amplification, it is appropriate to present the idea of SAW amplification. Amplification is based on the interaction of the surface acoustic wave and electrons in an adjacent conducting film. This concept of interaction was presented in the previous chapter. When the velocities of the wave and the electrons are sufficiently close, the electric field of the wave will modify

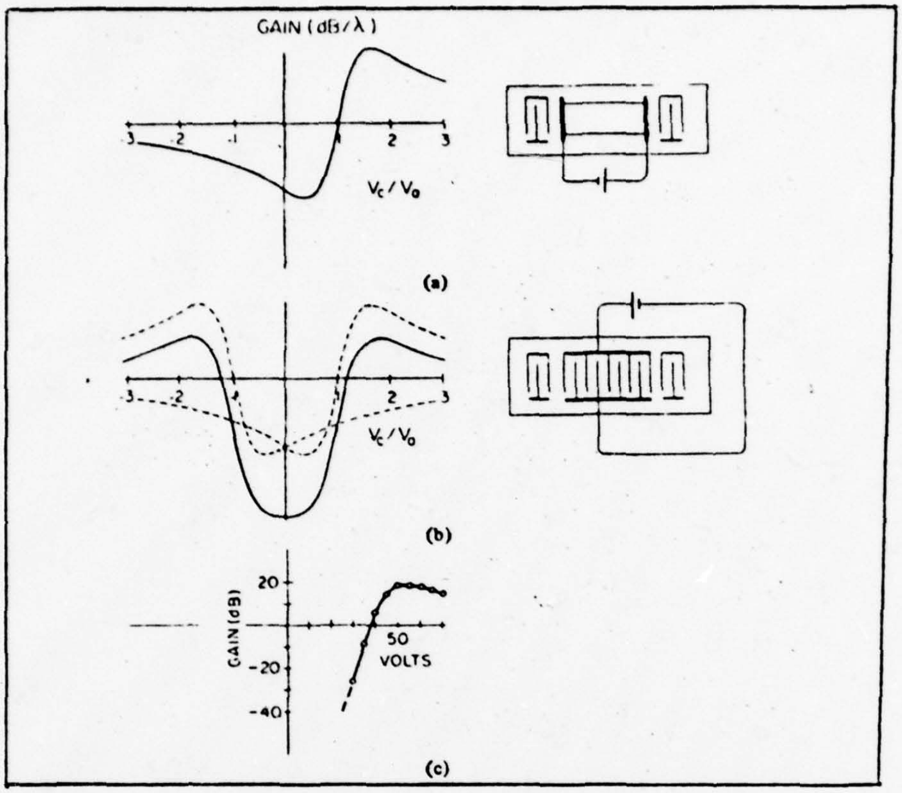

Figure 6. Surface-wave amplification. (a) Gain curve of a typical surface wave amplifier as a function of the ratio V_c/V_a where V_c and V_a are the carrier and acoustic velocities, respectively. (b) The solid line is the gain of the bidirectional amplifier. (c) The experimentally measured electronic gain is in agreement with the solid line of (b). (Solie, 1976:760)

the velocity of the electrons. To do this, energy is required. If the electrons speed up, the energy must come from the wave. Conversely, if the electrons slow down, energy is transferred from the electrons to the wave. This last transfer produces amplification of the wave.

The SAW convolver with bidirectional amplification (Solie, 1976: 760-764) involves an interaction a little more complex than those previously presented. The amplifying characteristics of the bidirectional SAW amplifier are presented in Figure 6, section (b). The dc bias is

applied to an interdigital electrode on a semiconducting film, instead of the two single-electrodes of the standard SAW amplifier (Figure 6, section (a)). The interdigital electrode (Figure 6, section (b)) has alternate segments of reverse polarity and hence alternating directions of amplification. The amplification in each direction is given by the dotted line. The solid line indicates the overall amplification, which, indeed, is symmetric about the vertical axis and therefore bidirectional. The internal amplification is a definite improvement over external amplification. Input amplification is limited by the saturation level. Output amplification amplifies the noise and signal equally, so nothing is gained. The internal amplification raises the figure of merit and hence increases the dynamic range. A typical efficiency (figure of merit) was found to be -12 dBm, which is a significant improvement over earlier versions of the SAW convolver.

Another improvement was found for the degenerate mode ($v_1=v_2$) of the convolver. Since the pattern does not vary with position for the degenerate mode, the center transducer can have any shape. If it is skewed (see Figure 7) by 15 degrees, experimenters found that reflections from the center transducer were routed out of the normal acoustic path. This lowered the distortion of the convolver (Solie, 1976:763).

In comparing the SAW convolver with non-SAW devices, some problems arise. First, there are no analog devices that directly implement the convolution of two different inputs. Correlation, the mathematical equivalent of convolution, is implemented by a mixer followed by an integrator. Mixers in the UHF frequency range do not have the large fractional band-

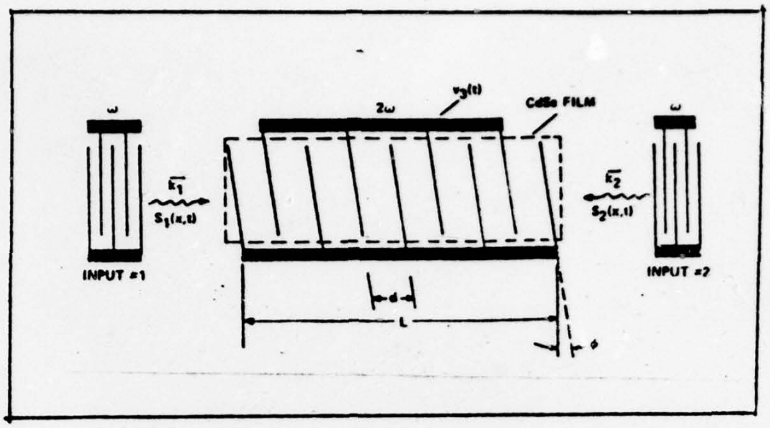

Figure 7. Degenerate Convolver with Bidirectional Amplification (Solie, 1976:762).

width of SAW transducers (e.g., 0.50). Comparisons can be made in power efficiency. A typical non-SAW mixer has a conversion loss (signal power output divided by signal power input, excluding the reference signal power) of 6.5 to 7.5 dB (Cole, 1975:120). This data corresponds to a figure of merit, F, of -26.5 to -27.5 dBm when a reference signal of 20 dBm is used. Although the SAW convolver with bidirectional amplification has a better F (i.e., -12 dBm), the regular SAW convolver has a much worse F (i.e., -83 dBm). Increases in the figure of merit also increase the dynamic range proportionally. The capability of calculating the convolution in real time is an advantage of SAW convolvers, in general, over other implementations. Although coherent optical systems (Goodman, 1977:29) can theoretically process the amount of information necessary for convolution in near-real time (e.g., a Fourier transformation of a 3,000 by 3,000 element array in nanoseconds), actual implementations of convolution are not in real time (Goodman, 1977:32).

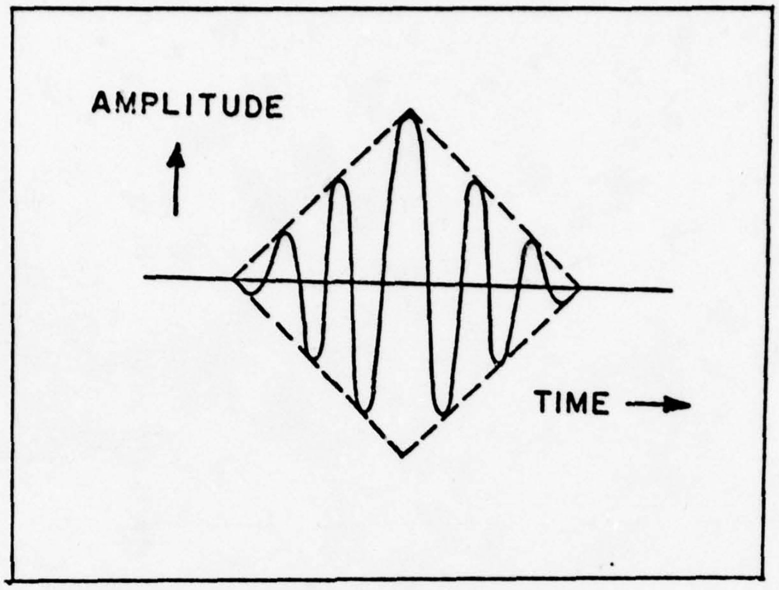

Figure 8. SAW Reference Pulse (Chodorov, 1977:10)

Analog-to-Digital Converter

The next device to be studied is an analog-to-digital (A/D) converter using a SAW-generated waveform as a reference voltage (Chodorov, 1977:8-37). In A/D converters, in general, an unknown fixed voltage is compared to a known reference voltage. The converter logic determines when the digital output is equivalent to the analog input. In this A/D converter, shown in Figure 9, an impulse is applied to a SAW delay line. Through the wave generating mechanism, the amplitude of the wave is determined by the interelectrode spacing. The resulting waveform is illustrated in Figure 8. The reference waveform is routed through comparator 0-X to a counter which is incremented for each positive peak in the reference waveform. One separate comparator (SIGN) determines the sign of the input while another comparator (STOP) stops the counter when the reference waveform is greater than the input. In order to have the correct number

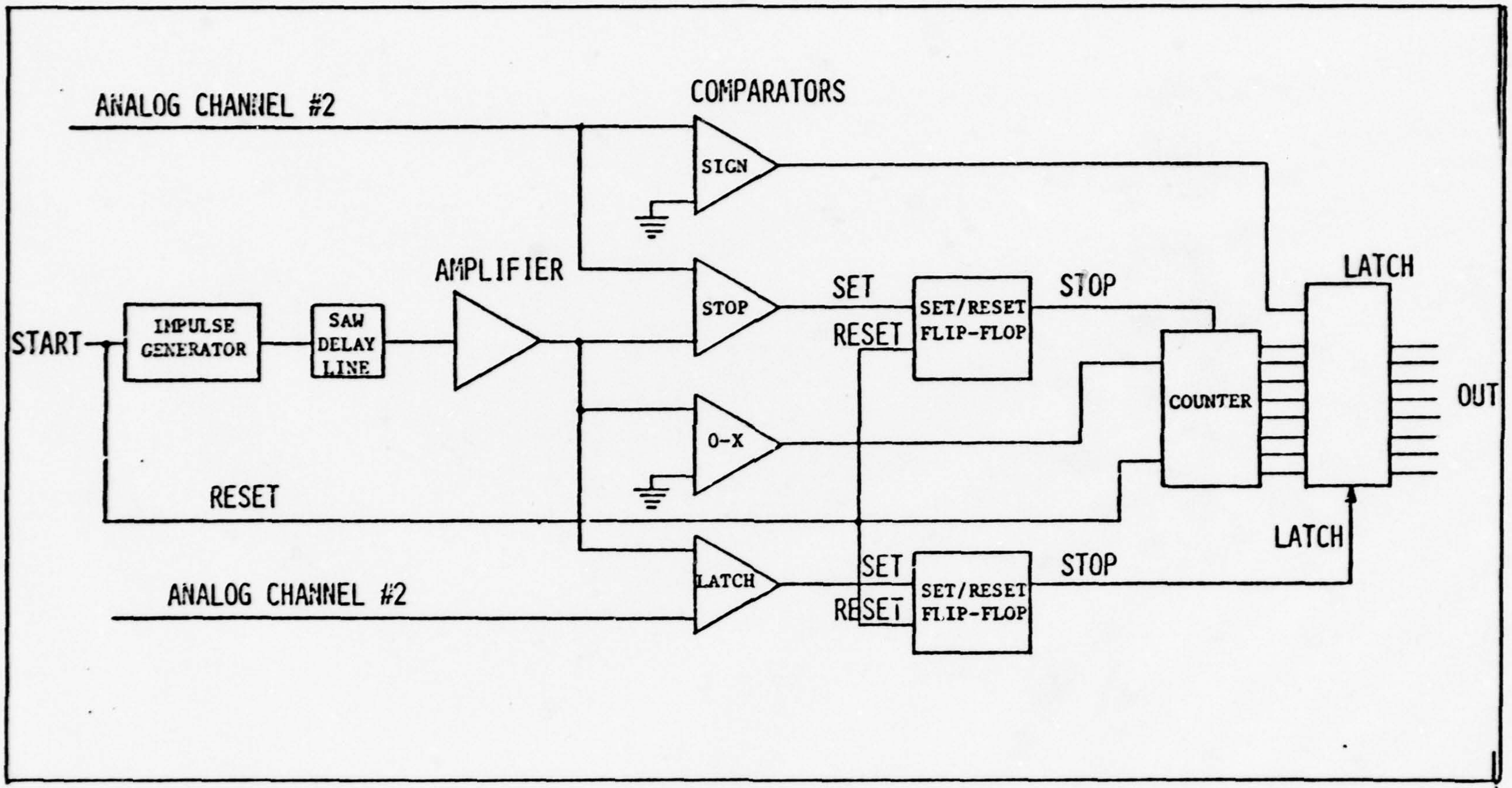

Figure 9. Block diagram for two-channel system (Chodorow, 1977:22).

of counts for the counter, there must be 2^N electrode pairs for N bits of output since each electrode pair represents one count of the counter.

One advantage of this conversion scheme is that the accuracy of the converter is not dependent on temperature. Although the temperature will vary the velocity of the wave, the number of quantization levels (counts) is only related to the number of electrodes. The linearity of the reference envelope is directly related to apodization, and hence is not temperature dependent. The only effect of temperature is to slightly change the conversion time, i.e., the time required to produce a digital output after the analog input is made.

Comparisons can be made between this and other A/D converters. One basis of comparison is conversion time. The A/D converter with the SAW reference waveform converts an analog signal to an 8 bit digital signal in 2 μsec. One source (Zuch, 1976:19) gives a range of conversion times for an 8 bit output resolution. The conversion times range from 40 nsec to 20 msec. In that range, the faster converters use the parallel and the successive approximation methods. The parallel conversion method uses a comparator for each quantization level and then uses logic to select the appropriate digital code. Successive approximation involves using the logic to determine the next choice of reference levels, based on the result of a previous comparison. Another source (Chodorow, 1976:14) compares the SAW-based converter with non-SAW, monolithic A/D converters and finds that the SAW-based converter is faster than all others except one. That one has a conversion time of 200 nsec. Some of those slower converters use successive approximation. One advantage of

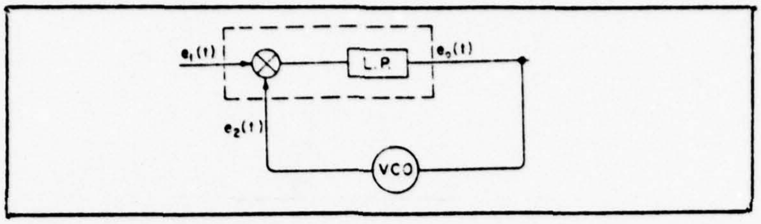

Figure 10. Phase-lock loop (Schachter, 1976:1053)

the SAW-based converter over the parallel and successive approximation converters is that the reference waveform can be used for converting more than one input at a time. The other two types of converters have little or not hardware savings for multiple inputs.

The dual-slope method most nearly approximates the methodology of the SAW devices and, in comparison, the SAW-based converter has a much better conversion time (i.e., 2 μsec versus 320 μsec). Comparisons of linearity errors, however, favors the dual-slope converters. The prototype SAW device has a linearity error of up to 2 percent, or over 2 least significant bits (LSB) (Chodorov, 1977:35) while the dual-slope converters have errors of only 0.01 percent (Zuch, 1976:24). By better manufacturing techniques the error in the SAW device can be reduced to less than 1 LSB (Chodorov, 1977:32) which is slightly worse than ½ LSB linearity errors in successive approximation converters (Zuch, 1976:27).

Phase-Lock Loop

The final device to be studied is a phase-lock loop (PLL) that uses SAW components (Schachter, 1976:1053-1057). Figure 10 is a block diagram of the PLL. The SAW components, a mixer and a low pass filter, are enclosed by a dashed block. The purpose of the PLL, in general, is to synchronize the oscillator with the frequency of the input. It is used

in signal tracking, frequency synchronization and FM demodulation.

To analyze the device operation, consider e_1 (t) and e_2 (t) (two voltages noted in Figure 10) to be a cosine wave with argument X and a sine wave with argument Y, respectively. The mixer output, then, is the product of the two waves, which can be expressed as the sum of two sine waves. One sine wave has an argument of X-Y and the other has an argument of X+Y. The cutoff of the low pass filter is chosen to eliminate the sine wave with argument X+Y which has the higher frequency. Voltage e_o (t) is, then, a sine wave with argument X-Y. The voltage controlled oscillator changes frequency according to its input voltage, e_o (t). When X-Y approaches zero, sin (X-Y) approaches X-Y so the oscillator frequency (contained in the argument Y) is changed toward the original input frequency and phase, X. But X has changed since the first mixing operation so the process is repeated. If the input was originally in the capture range of the loop (i.e., if X and Y were sufficiently close), lock will occur and X and Y will differ by a fixed amount. Note that if X-Y is not approximately zero and sin (X-Y) has a sign opposite of X-Y, the oscillator frequency will be forced away from the input frequency. Lock can still occur because the forces tending to align the frequencies may, on the average, be greater than the other forces.

Figure 11 shows the actual implementation of the PLL, excluding the voltage-controlled oscillator (VCO). These are the SAW components. The input and VCO voltages are combined in a transformer and transduced to a surface acoustic wave. As in the SAW convolver, mixing occurs in the PLL. Unlike the SAW convolver, however, the waves are travelling in the same

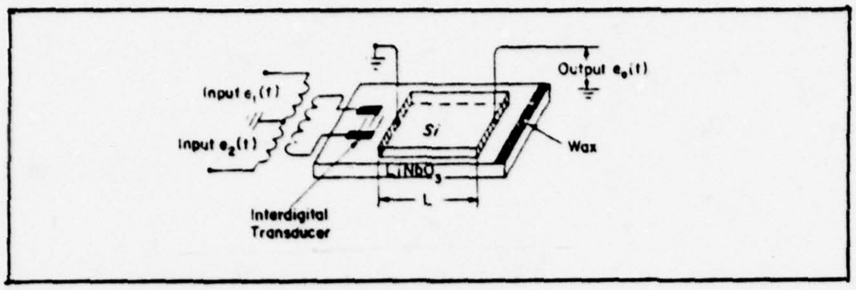

Figure 11. SAW components of PLL (Schachter, 1976:1054)

direction. The multiplication process was covered in the section on the SAW convolver. Low-pass filtering has not been covered and it involves the SAW-semiconductor interactions. It has been experimentally found that this interaction increases the efficiency of the mixing process by 30 dB (Kino, 1973:169). In addition, the low frequencies of the mixing are difficult to transduce using an interdigital transducer. As an example, a 10 KHz wave, in $LiNbO_3$ has a wavelength of approximately 35 cm (depending on the propagation direction). Just one pair of electrodes would require a 17 cm length of substrate and more pairs would be needed for efficient transduction. The length alone would make transduction using an IDT prohibitive. Transduction through the use of an adjacent silicon slab is possible due to the nature of the induced currents.

From the original discussion of the currents caused by the SAW-semiconductor interactions, it can be seen that the total current in the semiconductor is the sum of all the charges times their velocities. One way to calculate this current is to find the charge density and charge velocity for a small volume of the semiconductor and multiply by the volume. In nonlinear interactions, the charge density (or distribution) and the charge velocity in the volume are both, in part, proportional to the electric field of the wave at that point. Part of the velocity, however, is

due to the ambient electric field and part of the charge density is also not dependent on the wave (i.e., the charge density caused by doping impurity levels). At any one point, the product of charge density and charge velocity is, then,

$$(v_a + v_w)(n_a + n_w) = n_a v_a + n_a v_w + n_w v_a + n_w v_w \tag{3}$$

where v_a is the charge velocity due to the ambient electric field, v_w is the charge velocity due to the wave, n_a is the ambient charge density (i.e., not due to the wave) and n_w is the charge density due to the wave. By taking the volumes small enough, the summation becomes an integral over the area of the interaction.

To further reduce the complexity of the calculation, some simplifications can be made. Since, in Figure 11, the current is being taken from the ends of the silicon slab, the component of current normal to the slab (or parallel to the ends) can be ignored. The current perpendicular to the wave-propagation direction and parallel to the surface can also be ignored because there is no component of the electric field of the wave in that direction (there are only longitudinal and normal components). That part of current is then due only to the ambient electric field, and its effects are known or can be measured. This leaves only the component of current in the direction of the wave propagation. That component of current is

$$I_z = \int_0^L (n_a v_a + n_a v_w + n_w v_a + n_w v_w)\, d_z \tag{4}$$

where L is the length of the silicon slab. As before, the effect of the

ambient electric field and charge density can be calculated or measured, so the effect of $n_a v_a$ can be neglected. If n_a and v_a are essentially constant and the spatial wavelength is much less than L, a further reduction can be made. The latter assumption about the wave is generally true. Even waves of frequency 10 MHz (the lowest frequency that can be transduced by an IDT) have wavelengths of about 0.03 cm while L is approximately 1 cm. If both assumptions are valid, $n_a v_w$ and $n_w v_a$ would both be directly proportional to the wave amplitude and their integral over L would be approximately zero since the integral is over many spatial wavelengths.

The term $n_w v_w$ is the nonlinear term and accounts for the contribution of the wave to I_z. In the phase-lock loop in Figure 11, the wave is the linear sum of e_1 (t) and e_2 (t). Therefore the integral will involve the product

$$\left[e_1 (t) + e_2 (t)\right] \left[e_1 (t) + e_2 (t)\right] = e_1^2(t) + 2e_1(t)\, e_2(t) + e_2^2(t) \qquad (5)$$

which is proportional to the product $n_w v_w$. If e_1 (t) and e_2 (t) are sinusoidal, the square terms will involve dc terms and double spatial-frequency terms. The latter integrate to zero since the integration is over many wavelengths. The cross product involves the product of sinusoids which was presented in the original discussion of the PLL. Like the other high spatial-frequency terms, the term with the sum of the arguments integrates to zero. The difference term is integrated to provide the feedback for the VCO and the integral of the dc term can be accounted for by proper biasing.

Another way of looking at the filtering action is to consider the impulse response of the filter. Current flows in the semi-conductor whenever there is a wave in the piezoelectric just below the silicon slab. Since the impulse is under the slab for a distance L, or for L/V seconds, the current is a pulse of duration of L/V seconds. That pulse is the impulse response, by definition. The magnitude of the frequency response of the filter is, then, a sinc function with a first zero at V/L Hz. For V = 3448 m/sec and L = 1cm, the first zero is at 345 KHz. Varying the velocity (by choosing the piezoelectric material) or the length of the silicon will not significantly change the value of that zero.

The remaining major element of a complete PLL, the voltage controlled oscillator, is, in principal, no different in SAW and non-SAW designs. However, a complete PLL can be assembled from the combined interaction SAW device described above and a VCO, whereas conventional PLLs incorporate separate phase detector and filter elements, making the assembly more complex. The impedance levels, signal amplitudes, and other details may also dictate different VCO characteristics for the two types of PLLs.

Comparisons of the performance of the phase-lock loop using SAW components with non-SAW phase-lock loops could be misleading. Although one SAW-based PLL has demonstrated a large lock range (i.e., a frequency range over which the input and the VCO will remain "locked" or aligned) of $\pm$ 2 MHz about the 16.6 MHz carrier (Schachter, 1976:1057), the range also means more noise due to the increased loop bandwidth (Mills, 1971: AN46-4). Another performance indicator given by Schachter was total

harmonic distortion in demodulating an FM modulated 10 KHz sine wave from a 16.6 MHz carrier. The lowest distortion reported was slightly less than 2.5 percent (Schachter, 1976:1057) for a peak frequency deviation of 600 KHz. That percentage is not considered low for PLLs (Klapper, 1972:122). Yet many loops use additional filtering (called post-detection filtering) to reduce distortion whereas no additional filtering was used in the SAW-based PLL (Schachter, 1976:1056). It is misleading to compare this prototype PLL with more developed PLLs. A complete statement of the state of development of the SAW-based PLL is contained in Meng, 1975 in the bibliography.

Comparisons can also be made on a component basis. The SAW filter is capable of large bandwidths (e.g., 150 KHz) but cannot compete with an RC filter at lower bandwidths (e.g., 5 KHz). At the lower bandwidths the silicon slab would be too long. The basic mixing components were compared in the section on the SAW convolver. Mixing in the two SAW devices is through the same basic interaction in semiconductor medium and the two would be totally comparable for the SAW convolver that did not use amplification. That convolver was less efficient than the non-SAW mixer, on the basis of power-out versus power-in.

Conclusion

This chapter has presented some of the practical aspects of SAW technology. Specifically, losses occur in propagation and transduction. Distortion partially occurs from reflections from transducers and other surface discontinuities. Reflection can also have a beneficial effect, when it is controlled. The effect of the environment on surface acoustic

waves was also presented. These waves, in a SAW oscillator, are less affected by a high vibration environment than an electrical signal in a quartz crystal oscillator. Temperature can change many of the crystal parameters, and one of the results is a change in wave velocity. Neutron radiation reduces the efficiency of the interactions of the waves with electrons in a semiconductor. One of the mechanisms of this reduction is charged surface states. Like reflections, charged surface states can be beneficial, when controlled. These factors account for some of the non-ideal characteristics of the waves.

In order to gain a perspective on performance, three devices that use SAW components were presented. The performance of these devices was compared with the performance of either equivalent or similar non-SAW devices. The specific devices presented were a SAW convolver with bidirectional amplification, a A/D converter that uses a surface acoustic wave to generate a reference voltage, and a phase-lock loop that uses SAW components for mixing and filtering. Of the three, the SAW convolver with bidirectional amplification has the best comparative performance. The SAW A/D converter demonstrates better performance than converters using a similar conversion method (i.e., dual-slope). For large bandwidth signals, the SAW-based PLL has good performance even though the individual component performance may be inferior non-SAW components. Part of the reason that SAW devices performance demonstrated to date compares unfavorably in some respects to conventional PLLs is that these devices are early prototypes while the non-SAW devices are more highly developed. It should also be noted that each of the SAW devices has a very simple structure,

offering potential advantages in size, cost, and environmental ruggedness.

Further conclusions can be drawn from the performance of the various SAW convolvers. As previously discussed, when mixing is done in the piezoelectric medium, the power efficiency of the SAW convolver is -83 dBm, and when mixing occurs in the semiconductor medium the efficiency is increased by 30 dB. Another 41 dB is gained in efficiency by strengthening the wave-electron interaction by applying an external electric field to the semiconductor (i.e., the bidirectional amplification). The increase in power efficiency is a result of combining and strengthening the various interactions. Different combinations of interactions will be analyzed in Chapter IV.

IV. New Approaches

Although Chapter III provided some information about specific SAW device performance and deficiencies, many of the subjects covered could be expanded to include slightly different effects or interactions. The purpose of this chapter is to extend the analysis to new and more radical approaches to signal processing elements. The results of the amplified SAW convolver will be expanded to an analysis of the effect of external-electric-field-induced phase changes on mixing. In Chapter III, the reference waveform for the A/D converter was presented as being generated by a fixed SAW filter. Expansion of the analysis will include variable filters to produce a reference wave. Finally the analysis of the product of charge-density and charge-velocity, provided in the analysis of the SAW-based PLL, will be expanded to include variations in the ambient charge density.

Like the results of Chapter III, the results of this chapter will be tied to communications systems. However, here the analyses will address limitations in present communications systems. One constraint on the performance of a system using a VCO is due to the frequency instability of the VCO itself (Klapper, 1972:122). This instability might be reduced if a fixed, stable oscillator is used and a separate device is used to control frequency and/or phase. A varactor (voltage-controlled capacitor) can be used to control frequency, but there is no device that controls only phase. In a squaring loop receiver, there are limitations in implementation (or mechanization) due to the inability to achieve the combination of high frequency of a bandpass filter, high Q (because of a

low data rate) and the capability of adjusting the Q for varying data rates (Simon, 1973:6). In addition there is a need for an efficient square-law device after the bandpass filter. In another class of systems, the capability to select a relatively narrowband (i.e., 10 KHz) signal from a VHF signal (or from a IF signal in that frequency range) and amplify it would be a desirable feature, particularly if the circuit accomplishing this was simple. The applicability of SAW interactions to components addressing these problem areas is not immediately obvious, but, as the following sections demonstrate, considerable potential exists for improving on present standards of performance.

Delay or Phase Mixer

The effects of field-induced phase changes on the mixing process in a semiconductor are very different from the effects of amplification and have received much less attention in the literature (Crowley, 1977:558). Part of the effect was noted in the discussion in Chapter II of $\Delta v/v$ and the multistrip coupler. While the wave is underneath a metal film, the velocity of the wave decreases proportionally to the electromechanical coupling factor, k^2. The change in velocity is the same as a delay (or advance) or a phase change in the wave. The effect of the semiconductor is to allow movement of electrons to reduce the electric field of the wave, like the reduction caused by the metal film. Because of the distance between the semiconductor and the surface, and the limited mobility of electrons in the semiconductor, the reduction of the electric field and the change in velocity is not as much as for the metal film. As an example, for a metal film over yz-$LiNbO_3$ the velocity change is 2.4

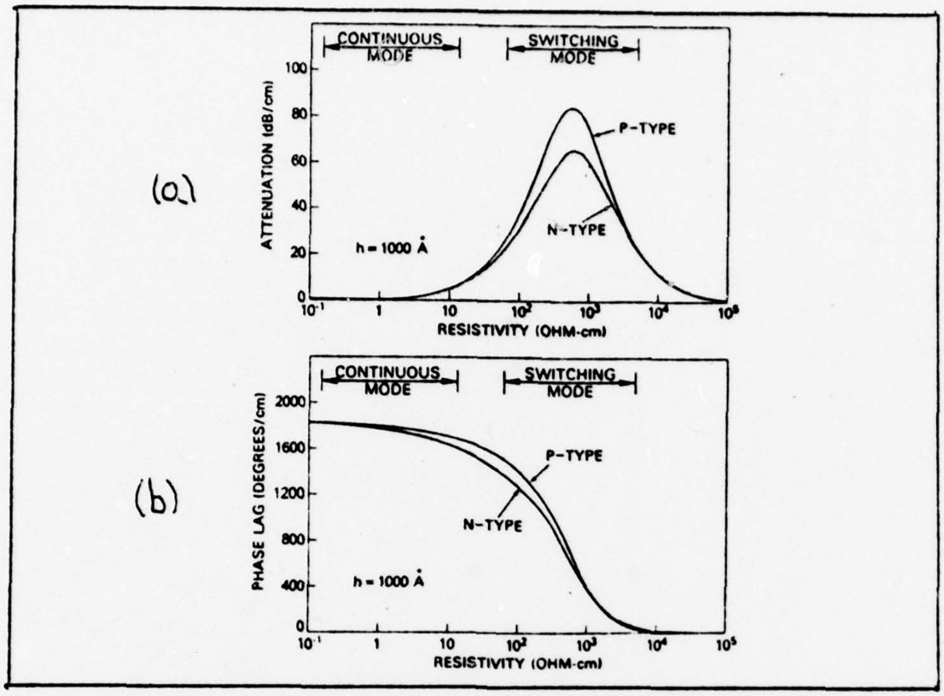

Figure 12. (a) Attenuation versus resistivity with proposed low-loss modes of operation. (b) Phase lag versus resistivity with proposed low-loss modes of operation. (Crowley, 1977:558)

percent (Slobodnik, 1976:593) while the maximum change for a silicon slab separated form yz-$LiNbO_3$ by an air gap of 1000°A is 0.76 percent (Crowley, 1977:558).

The percent change in velocity can be varied by applying an external electric field to the semiconductor surface. This is done by placing a metal plate on the side of the semiconductor opposite the surface and by grounding the bottom surface of the piezoelectric material. The electric field moves charges either toward or away from the surface, thus changing the surface resistivity (Many, 1965:129-163). With more electrons (lower resistivity) it is easier to reduce the electric field of the wave. Crowley provides a plot of attenuation and phase lag versus resistivity

for a silicon air-gap coupled to yz-$LiNbO_3$ with a gap of 1000 $\mathring{A}$ and at a frequency of 230 MHz. The graphs are provided in Figure 12.

Not addressed in Crowley's report was the possibility of a frequency change associated with the phase (or velocity) change. The reason for thinking that there might be a frequency change can be seen by comparing the surface acoustic wave with a simple harmonic oscillator of a particle on a spring. If the spring has a spring constant, K, and X is the displacement distance, then the potential energy stored in the spring is $KX^2/2$. The frequency of the oscillator is then proportional to $\sqrt{K/M}$ (Resnick, 1968:349) where M is the mass of the particle. For the surface acoustic wave, the electrical potential energy stored in the wave is proportional to k^2 which is approximately equal to $2\Delta v/v$. By reducing the velocity, the coupling factor, k^2 is also reduced, so the total potential energy of the wave (mechanical and electrical) is reduced to $1-k_1^2$, or $1-2\Delta v_1/v$, where k_1^2, is the equivalent reduction in coupling that is proportional to the velocity change Δv_1. If the simple harmonic oscillator and the surface acoustic wave were analogous, as far as frequency determination is concerned, the surface-acoustic-wave frequency would be changed by a factor of $\sqrt{1-2\Delta v_1/v}$ for a velocity decrease of Δv_1. The propagation constant w/v would then be proportional to $w\sqrt{1-2\Delta v_1/v}/V \ (1-\Delta v_1/v)$ for a decrease in velocity. But

$$\sqrt{1-2\,v_1/v} \approx 1-\tfrac{1}{2}\,(2\Delta v_1/v) + (1/2)\,(-1/2)\,(2\Delta v_1/v^2)^2/2 + \text{higher order terms} \quad (6)$$

The propagation constant, with the simplification, is equal to $(w/v) - (w/v)\left[\Delta v_1^2/2v^3\ (1-\Delta v_1/v)\right]$ or the propagation constant would increase for a decrease in velocity. If the frequency did not change, the propagation

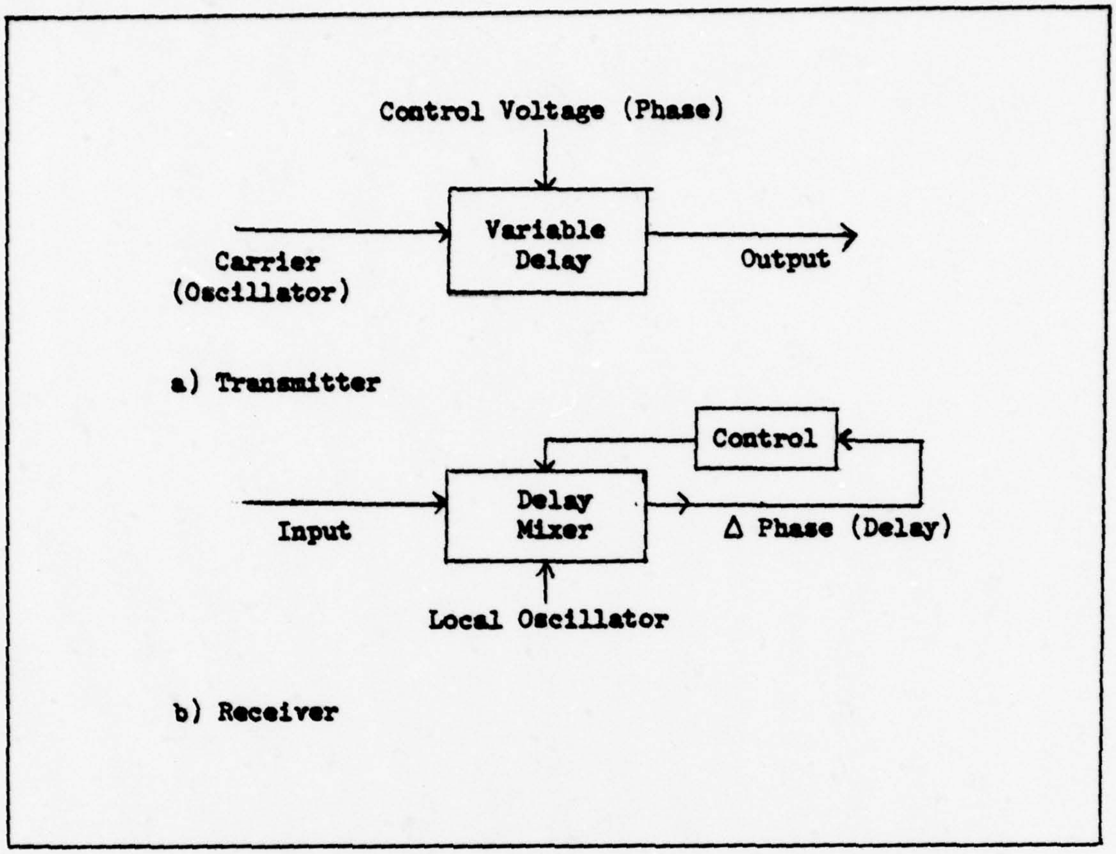

Figure 13. Block Diagram of Proposed Phase Modulation/Detection System

constant would be equal to $w/v\ (1-\Delta v_1/v)$ and would increase for a decrease in wave velocity. In this analysis Δv_1 is just a positive number and the direction of change is taken into account by the sign before the $\Delta v_1/v$. The experimental evidence (Crowley, 1977:559) agrees with the increase in propagation constant for a decrease in velocity. Therefore this model predicts that the frequency change will not occur.

The application of the phase or velocity change phenomenon which is of interest in this study is in the area of a voltage-controlled time delay (or phase shift). A proposed system is illustrated in Figure 13. A

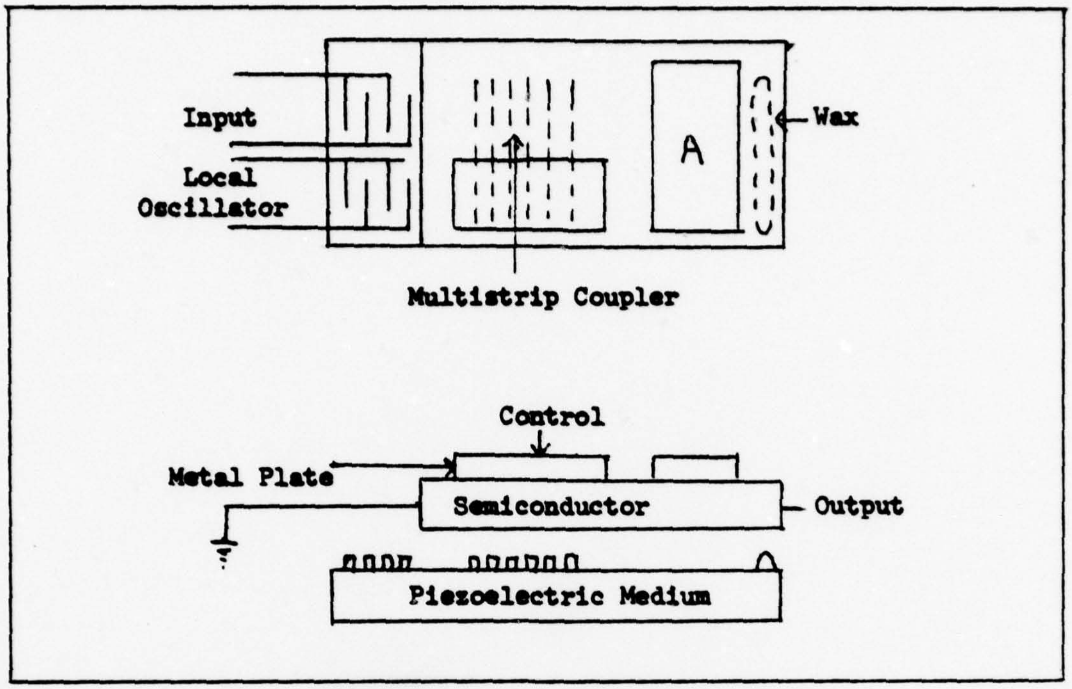

Figure 14. Delay Mixer

control voltage is used to encode the phase (or time delay) of a stable oscillator at the transmitter. At the receiving end, the input is delayed and mixed with a stable local oscillator. The delay is proportional to the phase (time delay) difference between the input and the local oscillator. As an example of the magnitude of voltages needed, in the Crowley experiments a +30v, 10 μsec pulse produced a 180° phase advance (Crowley, 1977:559) for a 1.2 cm interaction length on the silicon slab. At 230 MHz, that represents a relative time delay of 2 nsec.

The delay mixer itself is illustrated in Figure 14. Note the difference between that figure and the PLL in Figure 11. The combining of signals in the PLL is done by the transformer while signal combination in the delay mixer is done through a multistrip coupler. The reason for

the difference is to provide the differential phase (or time) shift. The multistrip coupler should be designed for half energy transfer to allow for uniform mixing through out the interaction region. In both devices mixing is done in the semiconductor medium. Further strengthening of the mixing could be obtained by placing another metal plate between the control plate and the wax (area A in Figure 14). The effect would theoretically be comparable to the effect of amplification on the SAW convolver.

Mixing in this device can be analyzed by using the previously developed form of the electric fields of the waves. Let the input wave be of the form exp j $(w_1 t - w_1 z/v_1 t \phi_1)$ and let the oscillator wave be of the form exp j $(w_1 t - w_1 z/v_2 + \phi_2)$. Then the mixer will form the sum and difference frequencies. The difference will be of the form exp j $\left[w_1 z (v_1 - v_2)/v_1 v_2 + \phi_1 - \phi_2 \right]$. The spatial integration, over z, will yield a function of $\phi_1 \phi_2$. The largest problems in this device would be converting the smaller phase-difference voltage to the larger control voltage and compensating for different attenuation levels caused by different phase (time) shifts (see Figure 12). The former could be solved by pulsing the mixer with the same voltage until a null is reached. The latter requires operating in the continuous mode area of the attenuation curve (Figure 12) where there is little attenuation, or operating on equi-attenuation levels on the switching-mode portion of the curve. Other methods of compensating for attenuation might be more difficult.

It thus appears that a particularly simple and compact implementation of the detection function in a phase modulation communication scheme is

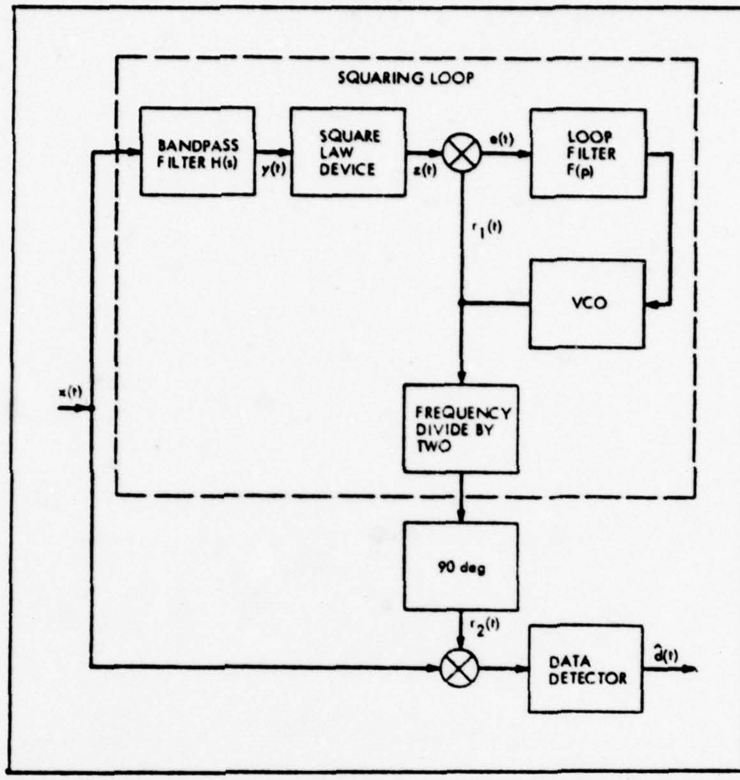

Figure 15. Squaring loop receiver (Simon, 1973: 6)

possible with a SAW component. Its similarity to other, well understood SAW devices gives some confidence that bandwidth, dynamic range, and power efficiency would be adequate to the demands of the application.

Variable Bandwidth Filter for Squaring Loop

The next area to be covered is the lack in conventional technology of filters which simultaneously provide high frequency (in the high IF range), high Q and adjustable Q. This corresponds to the analysis of a variable reference filter, where the reference generated is the suppressed carrier of a suppressed-carrier transmission. A block diagram of the squaring-loop receiver is given in Figure 15. In one example treated by Bell, a SAW resonator is tuned to give variable bandwidth (Bell,

1966:719). The untuned resonator has a center frequency of 140 MHz and a 3 dB bandwidth of 24 KHz for a Q of about 5,800. By tuning with a 0.16 μh inductor and a 3.7 pf capacitor the 3 dB bandwidth is changed to 72 KHz for a Q of about 1,900. Using a 0.355 μh tuning inductor increases the bandwidth to 253 KHz and decrease the Q to 550. The purpose of the filter is to maximize the signal-to-noise ratio of the suppressed carrier signal (Simon, 1973:6) and that ideal bandwidth is related to the data rate. This resonator would allow high frequency, high Q and the adjustable Q by adjusting the tuning inductor and capacitor. From Bell's examples, it appears that data rates of about 15 KHz and up could be used. To date, the emphasis in work on SAW resonators has been on extending the concept of fixed, high Q filter elements to higher frequencies than can be obtained with conventional bulk mode crystals. However, further work on the interaction of SAW resonant cavities with external reactive tuning and load components is a promising approach to the stated goal of electronically or mechanically adjustable bandwidth filters in the high IF frequency range.

Following the bandpass filter in the squaring loop receiver is a square law device. Ideally there should be a mechanism that generates waves proportional to the square of the input voltage (e.g., the electrostrictive effect). Unfortunately even for materials with high electrostrictive coefficients, like $SrTiO_3$ (Iamsakun, 1975:269), the effect is not strong enough. The next best approach is to increase the power to strengthen the second harmonic wave which results from the mechanical nonlinearity of a solid wave propagation medium. Slobodnik, 1969 pre-

sents the relative power levels necessary to get the second harmonic to the desired level (for $LiNbO_3$). Once again, a SAW component with the advantages of small size, built-in frequency selectivity, and low noise is a possibility which, moreover, can potentially be integrated with the acoustic band pass filter, keeping the information in acoustic form.

Narrowband Filter with Gain

In the section on phase-lock loops in Chapter III, equation (3) presented the various products of the ambient and the wave charge densities and charge velocities. One of the terms on the right was a product of the ambient charge density and the wave charge velocity. An interesting possibility arises as a result of varying the charge density from point to point as a function of the distance, z, along the acoustic path. For simplicity the charge density will be taken as cos az. Next consider a wave of the form $\sin(w_1 t - w_1 z/v)$. The product of the two is $\cos az \sin(w_1 t - w_1 z/v)$ which will give a sum and difference term. The difference term will be of the form $\sin\left[w_1 t - z(a + w_1/v)\right]$. If the spatial period is small enough, a spatial integration (of the form used in the PLL or the SAW convolver) will be non-zero. Moreover the spatial integration over anything less than one half of the spatial period gives increasing values, or the equivalent of gain. Actual gain will depend on the existing loss mechanisms (i.e., propagation losses and transfer of energy to the semiconductor medium) and possibly other presently-unknown loss mechanisms.

The key to the implementation of this device is establishing the varying charge density in the semiconductor medium. It can be done with

ion implantation techniques. To resolve a signal from a 200 MHz carrier on yz $LiNbO_3$ requires a spatial resolution capability of the ion-implantation process of 8 μm. This is presently possible. The region of useful gain is limited to one half of the resolved signal's wavelength. For a 12 KHz signal in yz $LiNbO_3$ that length is 14 cm.

Acoustic Integrated Signal Processing Components

The concept of a SAW system in which a number of signal processing steps are carried out on a signal which is propagated in acoustic form throughout has been proposed unsuccessfully for a number of years. The principal difficulties have remained the lack of effective waveguiding structures on highly anisotropic SAW media and the need to periodically amplify the wave to cancel propagation losses. A SAW "integrated circuit" remains impractical, but in view of the relatively complex, multiple-medium interactions discussed above, it may be asked if some degree of functional integration is appropriate.

Among the devices considered in this study are components which combine mixing and filtering functions and variable bandwidth filtering with square law detection or mixing. Additional possibilities include incorporating electronically variable phase control in one or both input signal paths of a SAW convolver and a variety of configurations in which gain could be added to passive signal processing elements. To summarize this brief treatment of a complex subject, it can simply be noted that integration of functions is one further area of investigation in extending the use of SAW components to solve system problems.

Conclusion

In this chapter several combinations of effects and interactions have been presented. Although it is difficult to predict performance in detail, some of the devices appear to be worthy of experimental investigation. Also fostered by these combinations a renewed possibility that there may be a SAW equivalent to the semiconductor integrated circuit. It would combine several operations on the propagating surface and not be plagued by the 3 dB loss incurred in transduction in and out of the SAW medium (i.e., from bidirectionality). It is still too early to tell if the SAW "integrated circuit" is possible but it seems that combining several operations adds to power efficiency. In any event, the wide assortment of mechanisms involving linear and nonlinear interactions of purely acoustic or mixed acoustic and electronic waves seem certain to continue to lead to new types of signal processing schemes and components.

V. Conclusions and Recommendations

In this study an attempt was made to find new ways of using SAW technology in communication systems. Although, as the information in Chapter I makes clear, SAW devices have been used in a wide variety of applications, it was felt that new information could suggest novel ways of using this technology. The results of Chapter IV confirm the basic hypothesis that many new device applications of SAW principles are possible.

The problem was approached by first analyzing the basic physics of the waves. It was found that what is considered basic is somewhat arbitrary. For example, reflection is a basic property used in SAW resonators but it may be of secondary importance in other SAW devices. It was also found that conflicting requirements require compromises and tradeoffs between desirable features. As an example, the use of a semiconducting material increases the efficiency of the mixing process but also makes the device more vulnerable to neutron radiation. Finally, it was found that certain facts about the basic physics can change. The use of the electrostrictive effect is an example. Early studies determined that the electrostrictive effect was not a very efficient method of transduction. Latter studies (Iamsakun, 1975) found that by dc biasing an electrostrictive material ($SrTiO_3$), the transduction efficiency was greatly improved and the material could be made to act like a piezoelectric material. Despite occasional ambiguities and analytical difficulties, the use of the basic physics as a guide to device performance

is a useful tool.

The study of actual SAW devices was also helpful. The studies in Chapter III showed that the interfacing of SAW devices with non-SAW devices and the judicious combination of both categories in a system is important. For example, in the A/D converter, the logic functions are most efficiently done by non-SAW devices. Comparison of SAW devices with non-SAW devices shows both strengths and weaknesses. The areas in which SAW devices particularly excel are high frequency (VHF to UHF), large bandwidth, and real-time processing. Weaknesses of SAW devices are also apparent. Although some of the basic processes (such as mixing in a piezoelectric medium) might be weaker than those in other devices, the use of a combination of processes makes the SAW device compare more favorably to a non-SAW equivalent. An example of the latter is the SAW convolver with bidirectional amplification.

Some caution, however, is necessary in making comparisons. It is very important to make sure that the devices are truly similar in intended function and that the state of development of each device is taken into account. Moreover, certain capabilities of SAW devices are not found in other devices, and methods of measuring performance for SAW and non-SAW devices are sometimes different. As an example, the figure of merit of the SAW convolver is not used as a measure of performance for the non-SAW mixer. For the non-SAW mixer, insertion loss is customarily used as a performance measure. These differences make it more difficult to make comparisons.

There are also difficulties in finding new approaches to using SAW

technology in communications systems. Of the many combinations of functions possible, just a few were investigated. Besides the number of wave properties and interactions that were studied, there is a question of how many functions can be put together and in what order. In looking at these alternatives the question of applicability must eventually be asked. That determination requires a thorough knowledge of both the application (i.e., communications) and the SAW technology. It was found that implementation problems are not as abundantly addressed in the literature as conceptual problems or experimental results. One reason for this is that many processing schemes are based on the capabilities of current implementations. The limitations are in the conceptual stage. All in all, the new approaches require an open mind and a thorough search of the literature. The three devices suggested in Chapter IV show promise and suggest that further studies could also be fruitful.

Some specific conclusions resulting from this work are the following:

1. The technology of SAW devices with relatively simple structure (in general, a patterned metal film on a suitable substrate) is well in hand, and the majority of the possible categories of device applications have been thoroughly investigated. It thus appears that future fundamental advances will involve more complex structures and interactions, an example being the addition of a separate semiconductor medium to the basic SAW configuration.

2. Specific comparisons can be made between similar SAW and non-SAW devices. The SAW convolver with bidirectional amplification has a better power efficiency than a non-SAW mixer (-12 dBm versus -27 dBm).

However, mixing in a piezoelectric medium or in an adjacent semiconductor medium (without amplification), has a much lower efficiency than mixing in a non-SAW device. The SAW-based A/D converter has a reasonably fast conversion time (2 μsec for 8 bit resolution) as compared with monolithic A/D converters, but has larger linearity errors (2 percent or 2 LSB versus 0.01 percent for a dual-slope converter or 1/2 LSB for a similar-conversion-time, successive-approximation converter). The SAW phase-lock loop has a large lock range ($\pm$2 MHz about a 16.6 MHz carrier). It also has more distortion (2.5 percent versus less than 1 percent) than a non-SAW PLL demodulator. On a component basis, the SAW components (mixer and filter) have worse performance. The mixer has a lower power efficiency and the filter cannot reach the low bandwidths (i.e., less than 5 KHz) of a non-SAW filter.

Recommendations For Further Study

As was previously stated, this study was by no means all-inclusive. There are many areas that deserve further investigation. Among those areas are the following:

1. The experimental investigation of the devices suggested in Chapter IV. These devices were a mixer that delays one input relative to a second input; a variable Q, high Q bandpass filter; and a filter that selects a signal based on an impurity pattern in a semiconductor.

2. Based on the suggestion in Chapter IV to use a SAW variable bandwidth filter in the squaring-loop receiver, extend this concept to use surface acoustic waves in a data-aided-loop system. In a data-aided-loop system, the detected data is fed back to a tracking loop (e.g., a squaring loop) to help maintain the carrier tracking.

3. Analysis of the use of dc biasing of the electrostrictive transducer (Iamsakun, 1975) to create large strings of encoded data.

4. Investigate whether frequency-mode coupling occurs in a piezoelectric-semiconductor SAW resonator. A similar effect was first noted in experimental results (Maines, 1970) for a bulk wave acoustic oscillator that used a piezoelectric semiconductor and the result was described as similar to lasing. The coupling was also treated theoretically (Zyuryukin, 1976).

5. Assemble a more comprehensive list of current and projected communication system signal processing algorithms, and continue the analysis, on a functional basis, of possible SAW implementations and comparisons to non-SAW versions.

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The purpose of this study is to suggest new approaches to the use of surface acoustic wave technology in communications systems. The problem was approached by considering the basic physics of the waves and their interactions with themselves, with electrons, and with photons. Three devices that used SAW components were analyzed on the basis of the basic physics, and their performance was compared with non-SAW devices, where possible. The three devices were a SAW convolver with bidirectional amplification, an A/D converter using a SAW-generated reference waveform, and a phase-lock loop using acoustic

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waves for the mixing and filtering functions. Based on the analysis of those devices, new approaches are suggested. The devices suggested were a mixer that delays one input relative to a second input; a variable Q, high Q bandpass filter; and a filter that selects a signal based on an impurity pattern in a semiconductor.

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